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Experimental and numerical investigation on the pressure pulsation and instantaneous flow structure in a nuclear reactor coolant pump

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ABSTRACT

The instantaneous vortical flow structure is one of the typical flow structures inside the nuclear reactor coolant pump (RCP), which would cause the unsteady pressure pulsations, vibrations of the unit and fatigue of components. Due to high safety requirement of the RCP during the actual operation of the nuclear power plants (NPPs), revealing instantaneous nature of vortical flow structure and its pressure pulsation becomes a crucial issue for studying the internal flow mechanism of the RCP. The purpose of this study is to shed comprehensive light on the pressure pulsation and instantaneous vortical flow structure in the RCP by using the experimental method and the numerical simulation method. Based on the result of comparison with the experiment and numerical simulation, it can be considered that the LES method can better identify instantaneous nature of vortical flow structures in the low frequency band. The instantaneous vortical flow structure is attached to the impeller RBPS (rotor blade pressure surface) and transient jet wake vortex flow structures between the impeller and diffuser under the rotor-stator interaction effect are fairly obvious by Q-criterion. On the other hand, in the axial-vorticity component distribution, the rotor-stator interaction effect between the impeller and diffuser cannot be clearly revealed. From the three-dimensional structures, the main vortex structures are in the front and back cavity of the right-hand side near the discharge nozzle and the right-hand side below the discharge nozzle in the spherical casing. Meanwhile, combined with pressure spectrum, it is convinced that their unsteady characteristic is the main reason that causes complex excitation frequencies in the low frequency band of the right-hand side near the discharge nozzle.

1. Introduction

The intricate instantaneous vortex is one of typical flow structures in the pumps, which would leads to significant flow instabilities, for instance unsteady pressure pulsation, vibrations of unit and fatigue of components, etc (Zhang et al., 2017; Posa et al., 2011; Posa et al., 2016; Yamanishi et al., 2007; Cheong, 2000). Especially for the nuclear reactor coolant pump (RCP) with quite high safety requirements in the nuclear power plants (NPPs) (Cho et al., 2014; De et al., 2014; Zhu et al., 2017), transient vortical structures are extremely complex and difficult to be revealed. Compared with the conventional spiral volute casing, RCP must be matched with spherical casing to guarantee the strength during the operation process (Baumgarten et al., 2010). Meanwhile, instantaneous vortical flow structures in the RCP are different from conventional pump (Ni et al., 2017a,b). Hence, it is really essential to identify and visualize the instantaneous nature of vortical flow structures in the RCP.

At present, investigations of the instantaneous vortical flow structures are rare in the RCP. Previous studies (Ni et al., 2016) had shown that the unsteady flow characteristics in the right side of the spherical casing were more complex than the left side in the RCP by using Large eddy simulations (LES) method (Ni et al., 2017a,b). Moreover, the vortex shedding from the diffuser blade trailing edge was analyzed in detail in the RCP. However, instantaneous vortical flow structures in previous studies were not fully revealed and the research method was single.

Some typical studies on the other pumps can be referred. Posa (Posa et al., 2011) reported LES method in a mixed-flow pump with an immersed-boundary method. They focused on the instantaneous flow dynamics in the impeller and found that the vortexes generated on the suction surface of the impeller blades and shed in the wake consequently. Zhang (Zhang et al., 2015) compared the simulation of the tip leakage vortex (TLV) trajectories and dynamics in an axial flow pump with the previous experimental results at different flow rates. Yamanishi (Yamanishi et al., 2007) explored the backflow vortex structure at the inlet of a turbopump inducer by using the LES technique, they found

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Nomenclature

Q_N	nominal flow rate
H_N	design head
Φ_N	nominal flow coefficient
Ψ_N	nominal head coefficient
n_d	nominal rotating speed
C_p	pressure coefficient
η	pump hydraulic efficiency
f_{BPF}	blade passing frequency
f_R	impeller rotating frequency
$RMSE$	root Mean Square Error

that the results obtained by LES methods agreed with experiments and backflow vortex flow features were analyzed in detail. Barrio (Barrio et al., 2010) investigated the unsteady flow in the near-tongue region in a volute-type centrifugal pump at different operating points by using the numerical method. They mainly focused on the relation between the pressure pulsations and fluctuating velocity field.

With the development of computational fluid dynamics (CFD), the computational data provide a large number of rich flow field data for the study. However, how to extract the complex vortex structures from these discrete data is a key problem to reveal the real flow field in the RCP. In order to reveal these complex vortex structures, many advanced methods for vortex identification and visualization have been developed and researched (Zhang et al., 2017; Wang et al., 2013; Haller, 2005; Šístek et al., 2012; Green et al., 2007; Kolář, 2011; Kolář, 2007). Zhang (Zhang et al., 2017) provided a practical guidance to the researchers for performing vortex identification in hydroturbines. Šístek (Šístek et al., 2012) compared three vortex-identification schemes (Q, λ_2, and TDM (triple-decomposition method)), which had been applied to the near-wake region of an inclined flat plate. The results showed that Q-criterion and λ_2-criterion performed better in removing the biasing effect of a local shear than TDM-criterion. Kolář (Kolář, 2007; Kolář, 2011) presented an update on vortex identification, vortex-identification requirements, and related vorticity aspects. He thought the vortex identification methods and their application to vortical flows should be combined with data acquisition especially in the direct numerical simulation (DNS) and LES which belong to the flow modelling and numerical simulation of transitional and turbulent flows.

In this paper, the RCP model pump is used as the research object. The experimental method and the LES method are combined to comprehensively analyze its unsteady pressure pulsations and vortical flow characteristics. Further, based on the vortex identification methods, the mechanism of transient flow structures in the RCP is preliminarily revealed.

2. Experimental setup

2.1. Main parameters of model RCP

The full-scale prototype RCP is the next generation nuclear reactor coolant pump, which employed for a 1400 MW power station unit in china (CAP1400). In this study, the test system had to meet the demanding requirements, thus it was decided to build a model pump (on a scale ≈ 1:3), which called model RCP. The main design parameters of the model RCP is shown in Table 1. In this paper, we mainly concern hydraulic components of the model RCP, thus the geometry of the model RCP studied in the present work are shown in Fig. 1(a), which consists of the impeller, diffuser and spherical casing. The impeller and diffuser consist of the hub, shroud and blade. In order to more accurately express the impeller and diffuser, Fig. 1(b) shows the detail information of Fig. 1(a). From Fig. 1(b), the blades of impeller are defined A–D and the blades of diffuser are defined 1–12. Meanwhile, RBPS is rotor blade pressure surface and RBSS is rotor blade suction surface. In the diffuser, SBPS is stator blade pressure surface and SBSS is rotor blade suction surface. Further, Fig. 1(c) shows the flow domain of the model RCP, including inlet flow domain, the impeller flow domain, the diffuser flow domain, spherical casing flow domain and outlet flow domain, respectively.

2.2. Test loop

The experiment of hydraulic performance in the model RCP was carried out in the test rig and Fig. 2 shows the experimental closed-type test rig. In order to realize the non-contact optical measurement of the model RCP in the future, components including diffuser and spherical casing must be made of organic glass to make the laser through the inside of the model RCP. Meanwhile, for this RCP with complex boundary, some special improvements were necessary. The water jacket with organic glass was set outside of the spherical casing to compensate for the refractive index and increase the measurement region. In the closed-type test rig, the water tank was set in the model RCP inlet, which could smooth the flow field of the test rig. Two pressure gauges were mounted on the model RCP inlet piping and outlet piping, respectively, in order to obtain the model RCP head with the measurement accuracy of 0.1%. The electromagnetic flow meter was installed in the test loop to control the flow rates of the model RCP on various conditions with the precision of ± 0.2%.

To attain unsteady pressure pulsation signals for comparison with LES method, seven fast-response piezoelectric pressure transducers, which are PCB113B27 series, were mounted around the spherical casing, from Fig. 3 can be seen. The monitoring point namely C8 and C12 are mounted on the discharge nozzle. The monitoring point namely W1, W3, W4, W5 and W7 are mounted on the spherical casing wall.

3. Numerical methodology

3.1. Solution method

In order to obtain more accurate instantaneous nature of vortical flow structures in the RCP, large eddy simulation (LES) method is applied in this study (Posa et al., 2011; Zhengjun et al., 2012). Filtered governing equations are discretized by the finite-volume scheme. Before unsteady simulation, the steady simulation with standard k-ε turbulence model is adopted. The coupling between pressure and velocity is established by means of the SIMPLEC scheme. For unsteady simulation, the bounded central differencing spatial discretization scheme is available for the momentum equations in the pressure-based solver. The second order implicit transient formulation is implemented to guarantee the accuracy. LES of turbulent flow in pumps relies heavily on the quality of the chosen subgrid-scale (SGS) models due to the limited grid

Table 1
Main design parameters of the model RCP.

Parameters	Value
Nominal flow rate Q_N	0.236 m^3/s
Design head H_N	12.7 m
Nominal flow coefficient Φ_N	$Q_N/(u_2R_2^2) = 0.63$
Nominal head coefficient Ψ_N	$gH_N/u_2^2 = 0.29$
Nominal rotating speed n_d	1480 r/min
Pressure coefficient C_p	$A/0.5\rho u_2^2$
Impeller blade number Z_i	4
Diffuser blade number Z_d	12
Impeller inlet diameter D_1	221 mm
Impeller outlet diameter D_2	268 mm
Impeller outlet width b_2	84 mm
Peripheral velocity at impeller exit u_2	20.8 m/s
Casing diameter D_3	637.5 mm